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ELECTRIC DISCHARGE COAXIAL LASER POWER MEASUREMENT

Arnold L. Augustoni

September 1986

Final Report

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This report presents a theoretical and empirical treatment of the power-measuring technique used in determining the output power of the Electric Discharge Coaxial Laser (EDCL). Errors in power measurement associated with the diagnostic beam splitter were investigated. These areas included errors associated with the removal of the beam splitter for storage overnight and the repositioning of the beam splitter the following day, and the introduction of possible errors as a result of interference between the beams reflected from the front and rear surfaces of the beam splitter.

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SUMMARY

The KCl beam splitter reflectance factor for determining Electric Discharge Coaxial Laser (EDCL) output power is 0.0682. The EDCL power measurement technique has a ±6.4 percent total system uncertainty. The errors contributing to the system uncertainty are as follows:

a. Errors associated with the Coherent Radiation Laboratory (CRL) 213 power meter are on the order of ±4 percent absolute accuracy.

b. Errors associated with the 213 power head are extremely small--less than ±1 percent for power heads with undamaged absorption plate coatings; however, this error may be much higher for power heads with damaged coating. The magnitude of this error depends on the extent of the damage to the absorption plate coating.

c. Errors associated with beam interference in the diagnostic leg are small, on the order of ±2 percent, and do not present a significant source of error in the EDCL power measurement.

d. Errors associated with the beam splitter reflection are on the order of ±3.6 percent.

e. Errors associated with the positioning of the beam splitter, angle of incidence, are less than ±1 percent.

The EDCL is not linearly polarized.

ACKNOWLEDGEMENTS

The author wishes to express thanks to SSgt John Kelly for his assistance in the performance of experiment 5 and to Maj Thomas Y. Edwards and Lt Steven Townsend for their inputs and direction.

CONTENTS

INTRODUCTION

Historically, laser output power measurements for the EDCL were obtained using the arrangement shown in Fig. 1. A portion of the output beam was split off by a 6-in-dia, 1.2-cm-thick, uncoated potassium chloride, KCl beam splitter, at an angle of approximately 18-deg incidence. The reflected beams were collected and focused to a power detector by a silver-coated copper mirror. The power in this split-off portion of the beam was measured by a Coherent Radiation Laboratory (CRL), Model 213 direct absorption water-cooled power head and power meter. The split factor used for this arrangement was 0.068. The laser power was then calculated by

$$Po = \frac{Pm}{0.068}$$

where

Po is output power of the laser

Pm is power measured in the split

The transmission losses in the beam splitter due to absorption and scattering were assumed to be very small. The transmitted power through the beam splitter was calculated by

$$Pt = (1 - 0.068)\ Po$$

$$Pt = 0.932\ Po$$

where

Pt is transmitted laser power

Po is output power of the laser

The above technique has been used to determine EDCL power output and to calculate transmitted laser power for many years. Concerns over power

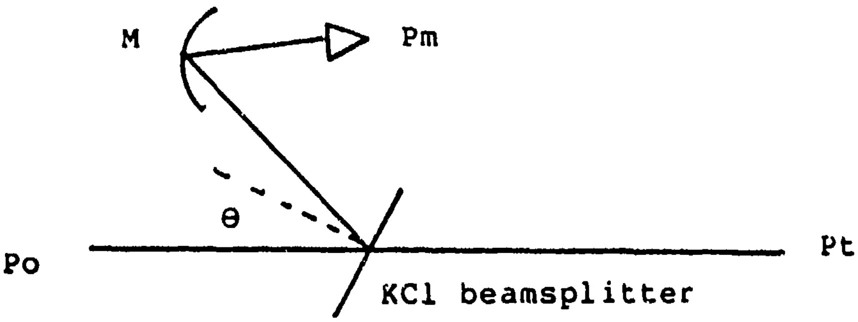

Figure 1. Optical layout for historic power measurement technique.

measurement errors have centered on the accuracy of the Model 213 power measurement system (power head and power meter). Several Model 213 power measurement systems are used with the EDCL. Each power head is matched and used only with its associate power meter. Each 213 power head and power meter is calibrated against a National Bureau of Standards secondary, BB2, maintained at the Air Force Measurement Standards Laboratory, Aerospace Guidance and Metrology Center, Newark Air Station, Ohio. Each Model 213 is calibrated routinely on a 12-mo cycle. The uncertainty associated with the Model 213 is quoted by the calibrating authority to be ±4 percent.

The KCl beam splitter is removed from the diagnostic layout routinely for storage in a desiccant cabinet when not in use. Its replacement in the diagnostic layout uses markings on the optics table for prepositioning, and a helium neon (HeNe) laser is used to align the reflected beams to the 213 power head. Both the collecting mirror and the 213 power head are fixed to the optics table. Error due to the positioning of the KCl beam splitter had been assumed to be small. The uncertainty associated with this power measuring technique had been assumed to be on the order of ±8 percent.

BEAM SPLITTER INTERFERENCE ERRORS

Concern has been expressed about possible errors in power measurements using the above power measurement technique (Ref. 1). These errors may be due to interference between the front surface reflection and the rear surface reflection from the KCl beam splitter (Ref. 1). The magnitude of this error has been estimated to be as high as ±13 percent for the beam splitter arrangement used with the EDCL (Ref. 1).

The estimate is based upon a monochromatic, narrow bandwidth, 10.6-μm laser beam incident on a 1.2-cm-thick, uncoated KCl beam splitter at an 18-deg angle of incidence, setting up fringes across the beam front. The magnitude of the error is somewhat dependent upon the spectral bandwidth of the laser. The greater the spectral bandwidth, the less the error in reflection due to fringe interference. This reduction in the interference error is due to an averaging effect of the fringe patterns. The spectral bandwidth required to achieve significant averaging is 4 GHz (Ref. 1).

The EDCL is not monochromatically pure; that is, it does not operate on a single emission line, but rather on many high-order transverse modes simultaneously (Ref. 2). The frequency separation between each of these modes is given in Ref. 3 as a function of cavity length.

$$\Delta = \frac{c}{2 L n}$$

where

- c is the speed of light
- L is the cavity length
- n is the index of the medium
- Δ is the mode separation

For the EDCL, the separation length between the intercavity optics is 1.82 m (Ref. 4). The index of refraction of the gas medium is assumed to be 1.000. The mode frequency separation associated with the EDCL can be calculated as

$$\frac{3 \times 10^{8} \text{ m/s}}{2(1.82 \text{ m})(1.0)} = 82.4 \text{ MHz}$$

The number of allowable frequencies or modes of oscillation can be determined from the cavity length (Ref. 5).

$$N = \frac{2\,n\,L}{\lambda}$$

where λ is the wavelength.

For the EDCL 1.82 m long,

$$\frac{2(1)(1.82 \text{ m})}{10.6 \times 10^{-6} \text{ m}} = 172 \times 10^{3} \text{ modes}$$

This represents the number of allowed modes of oscillations due to the geometry of the laser cavity. The number of modes contributing to the spectral composition of the emitted light is considerably less, however, due to intercavity losses. The number of emission lines of the EDCL is not known; however, it is believed to be high, as evidenced by the "flat top" profile of the beam.

The spectral bandwidth of the EDCL can be estimated by taking the product of the mode separation frequency and the number of modes believed to be operating simultaneously. If the number of EDCL modes is 50 or greater, the spectral bandwidth criteria for significant averaging, 4 GHz, is satisfied.

INVESTIGATION OF INTERFERENCE ERRORS

Several experiments were performed in an attempt to determine if beam interference errors are being introduced in the EDCL power measurements.

Experiment 1--The EDCL output, from shot to shot, is known to be stable to within ±2 percent for a fixed laser power setting. If interference errors on the order of ±13 percent are being introduced into the EDCL power measurements as a result of slight changes in the angle of incidence on the beam splitter, then this error should be measurable, as the angle of incidence is varied slightly, with the laser output fixed to within ±2 percent.

The KCl beam splitter was initially set up for a 15-deg angle of incidence and the laser was set up so that approximately 840 W were incident on the 213 power head in the diagnostic leg. The angle of incidence was varied slightly with the micrometer adjustment on the beam splitter mount. A total of 26 power runs were performed through an angular change of 0.5 deg. The power measurements varied by ±3.6 percent over the 26 runs, while the angle of incidence was changed from 15 deg to 14.5 deg.

The change in the power measurement reading of ±3.6 percent, over a 26-run laser series, is close to the variation one would expect to occur over a laser test series of this length. If beam interference errors are present, the results of this experiment indicate that they are on the order of ±2 percent, and do not present a significant source of error. Additionally, this result implies that the spectral bandwidth of the EDCL is close to that needed for significant averaging to occur.

Experiment 2--Effects of angle of incidence on the 213 power head.

Angle of incidence dependency for the 213 power head was investigated to determine if variations in this angle would introduce errors in the EDCL power measurements.

The experiment layout is shown in Fig. 2. The main transmitted power beam was focused to the Model 213 power head by a KCl lens. The spot size on

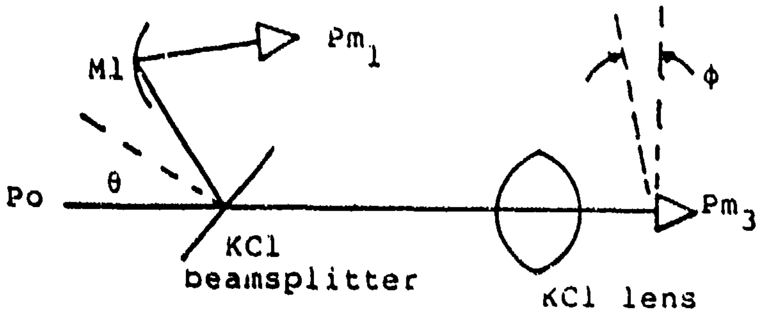

Figure 2. Optical layout for Experiment 2.

the 213 power head was 2 cm in diameter, which is similar to the spot size used in the diagnostic leg. The 213 power measurement system is limited to measuring laser powers up to and including 1000 W. The EDCL is generally operated in the 2-kW to 15-kW output power range. To reduce the EDCL output power to a level which could be safely measured by the 213 power meter, the EDCL was operated at lasing threshold. The power incident on the 213 power head was about 500 W. The angle of incidence on the 213 power head was varied over the range of normal to within 10 deg of normal. The normal measurement variation, for 22 laser runs, over this range of incidence angles was ±3 percent. This variation is somewhat higher than the variation in the EDCL output, and may be the result of a decrease in the EDCL power stability, from shot to shot, at threshold power levels.

The above experiment was repeated, with the EDCL operated at an output power level known to be stable, from shot to shot, to within ±2 percent, with the 213 power head placed in the diagnostic beam.

Experiment 3--The power in the diagnostic leg was on the order of 525 W. The angle of incidence was varied from normal to 10 deg, with the laser set for a fixed output.

The power measurement, for a 30-shot series, varied by ±2.8 percent. The variation in the power measurement is close to the ±2 percent laser power variation expected at this power level. This may indicate that a small error, on the order of ±1 percent, can be associated with the angle of incidence on the 213 power head.

The 213 power head absorption plate used in the above experiments had some slight damage to its coating. Possible differences in local absorption across the absorption plate may account for the above results.

<u>Experiment 4</u>--Experiments 2 and 3 were repeated using a new 213 power head, with no apparent damage to the absorption plate coating. The results were a ±1.5 percent variation over the same angular change, with the EDCL output power fixed to within ±2 percent.

The above result indicates that power heads with no damage to the absorption plate coating exhibit no variations in response as the incident beam impinges on varying areas of the absorption plate. Power heads with some damage to the absorption plate coating will exhibit a variation in power measurements in response to changes in local absorption within the incident beam area of the absorption plate as the beam impinges on varying areas of this plate.

Based upon the above experiments, the variation in the 213 power measurements can be expected, if areas of damage to the absorption plate coating exist.

BEAM SPLITTER PLACEMENT ERRORS

Concern has also been expressed about the possible introduction of errors in the EDCL power measurement as a result of slight changes in the angle of incidence on the KCl beam splitter arising from its daily removal for storage. These errors could occur because of a failure to reposition the KCl beam splitter precisely each time it was replaced. It was assumed that, if the technician followed the procedure stated previously, the error in positioning the KCl beam splitter would be no more than ±5 deg and would probably be much less.

The percentage of light reflected by the KCl beam splitter depends on the angle of incidence, the index of refraction of the beam splitter material, and the polarization of the electric field vector. The polarization depends upon whether the electric field vector is polarized in the plane of incidence or perpendicular to the plane of incidence. The EDCL has no polarization control elements and is therefore believed to have no favored polarization. It was assumed that the EDCL is nonpolarized, with 50 percent of the power in each of the two polarization orientations. The percentage of the reflection for each polarization can be calculated from Fresnel's equations as a function of the angle of incidence and the angle of refraction.

The reflectivity, r_s, for perpendicular polarization is given by

$$r_s = \frac{\sin^2(\theta_i - \theta_r)}{\sin^2(\theta_i + \theta_r)}$$

where

θ_i is the angle of incidence

θ_r is the refraction angle

The reflectivity, r_p, for parallel polarization can be expressed as

$$r_p = \frac{\tan^2 (\theta_i - \theta_r)}{\tan^2 (\theta_i + \theta_r)}$$

Snell's Law relates the refraction angle to the angle of incidence and the index of refraction of the incident and transmitting media.

$$n_i \sin \theta_i = n_r \sin \theta_r$$

where

n_i is the index of the incident medium
n_r is the index of the transmitting medium

The index of refraction for air is assumed to be 1.0000 and the index of refraction for KCl was found to be 1.454 (Ref. 5). Hence, for KCl the refraction angle is related to the angle of incidence by

$$\theta_r = \sin^{-1} \left[\frac{\sin \theta_i}{1.454}\right]$$

Combining Snell's Law with Fresnel's equation allows for the calculation of the reflectivity of the KCl as a function of the angle of incidence in both polarization orientations, but this gives the value of the reflections for only one surface. Since there are two surfaces of the KCl reflecting part of the incident beam, and since it was assumed that 50 percent of the incident power resides in each of the polarization orientations, then the total reflectivity can be expressed as the sum of r_s and r_p.

$$r_{total} = r_s + r_p$$

The reflectivity of the KCl beam splitter was solved for angles of 10-, 15-, and 20-deg incidence and is presented in Table 2.

Table 1. Reflectivity as a function of angle of incidence.[a]

θ_i	r_s	r_p	r_{total}
10	0.03569	0.03279	0.06848
15	0.03762	0.03098	0.06860
20	0.04049	0.02840	0.06894

[a]Calculated values of reflectance.

Assuming a ±5-deg change in the angle of incidence on the KCl beam splitter gives rise to an error of

$$\% \text{ ERROR} = \frac{0.06894 - 0.06848}{0.06860} \times 100 \%$$

$$\% \text{ ERROR} = \pm 0.67 \%$$

The magnitude of this error is such that a change of ±5 deg in the angle of incidence contributes slightly to any error in the power measurement.

The reflection was calculated for an 18-deg angle of incidence and was found to be 0.0687705. This reflectivity adjusted for the mirror loss is 0.06808, which is close to the split factor used in the EDCL power measurement calculation.

INVESTIGATION OF PLACEMENT ERRORS

The reflectivity factor, used to determine EDCL output power levels, is based on the assumption that the EDCL is not linearly polarized. If the EDCL did have a favored polarization, then the split factor being used would be in error by 14 percent. To verify this assumption, the following experiment was performed.

Experiment 5--If the EDCL is linearly polarized, then the percentage of reflection will change significantly as the angle of incidence on the KCl beam splitter is adjusted from 18 deg to Brewster's angle. The Brewster angle for KCl was calculated to be 55.5 deg.

Fresnel's equations were solved for both the 18 deg and 55.5 deg incidence angles. If the laser is perpendicularly polarized, then the percentage of reflection at Brewster's angle will be 25.622 percent. If the beam has a parallel polarization, no light will be reflected at this angle. However, if the EDCL is randomly polarized, then the percentage of reflection at 55.5 deg will be 12.811 percent.

The differences in reflectivity are large enough to be able to readily discriminate which of these polarization assumptions is valid. This is accomplished by making power measurements in the diagnostic leg, with a beam splitter angle of incidence of 18 deg and 55.5 deg. Because of the large angle and an EDCL beam diameter of 90 mm, a 10 in diameter KCl was selected for the experiment.

The 10 in KCl beam splitter was set initially at an angle of incidence of 18 degrees using a protractor and the HeNe alignment laser. The Laser was operated at approximately 3.5 Kw. The power in the diagnostic leg was measured on three successive laser firings with readings of 235.9 watts, indicating a stable, repeatable output power of 3,430 watts.

The KCl was then oriented for a 55.5 deg angle of incidence and the power in the diagnostic leg was again measured for three successive laser firings.

The power measured was 425.6 watts. The ratio of the power measured in the diagnostic leg to the output power of the laser should yield the reflectivity of the beam splitter at this angle.

This ratio indicates a reflectivity of 12.4 percent, which compares quite well with the predicted reflection of 12.8 percent for nonlinear polarization. The error between the calculated value and the measured value is 3.2 percent, which is well within expected experimental error range.

The results of this experiment indicate that the historic assumption that the EDCL is not linearly polarized appears to be indeed valid.

Empirical determination of the KCl beam splitter reflectivity

With reference to Fig. 3, the power measured by Pm1 can be expressed as

$$P_{m1} = r_1 \, r_{bs} \, P_{out}$$

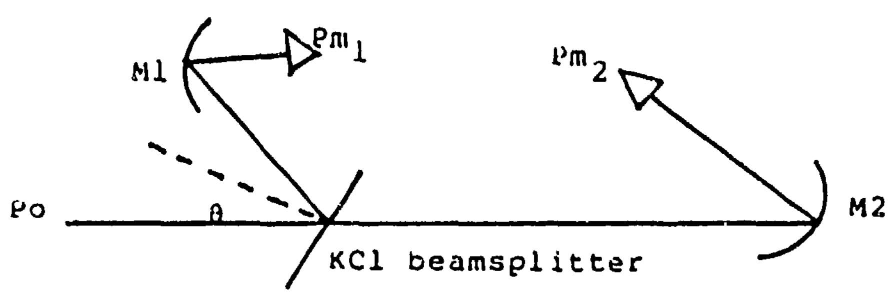

Figure 3. Optical layout for determination of beam splitter reflectivity.

where

> P_{out} is the laser output power
>
> P_{m1} is the power measured in the split
>
> r_{bs} is the reflection factor of the beam splitter
>
> r_1 is the reflection factor of the focusing mirror, M1

The power measured by P_{m2} can be expressed as

$$P_{m2} = r_2 T_{bs} P_{out}$$

where

> T_{bs} is the transmission factor of the beam splitter
>
> r_2 is the reflection factor of the focusing mirror, M2

The absorption loss for a 1.2-cm-thick KCl beam splitter can be calculated

$$\text{Loss} = 1 - e^{-ax}$$

The absorption coefficient for KCl is 0.0005 cm^{-1} (Ref. 4).

$$\begin{aligned}\text{Loss} &= 1 - e^{-(0.0005/cm)(1.2\ cm)} \\ &= 1 - 0.99940 \\ \text{Loss} &= 0.0006\end{aligned}$$

The power lost in the KCl beam splitter is on the order of 0.06 percent and can be considered zero. The transmission factor can then be expressed in relationship to the reflection factor.

$$T_{bs} = 1 - r_{bs}$$

which can be incorporated in the expression for P_{m2}:

$$P_{m2} = r_2 (1 - r_{bs}) P_{out}$$

The output laser power can be expressed in terms of P_{m1} and P_{m2}, which in turn can be equated to each other.

$$\frac{P_{m1}}{r_1 r_{bs}} = P_{out} = \frac{P_{m2}}{r_2 (1 - r_{bs})}$$

The beam splitter factor can be expressed in relationship to the power measured by P_{m1} and P_{m2}.

$$r_{bs} = \frac{1}{\dfrac{r_1 P_{m2}}{r_2 P_{m1}} + 1}$$

The reflectivity of mirrors M1 and M2 are believed to be 0.99 and 0.98, respectively. The value for the beam splitter reflection can be experimentally determined by measuring the power at P_{m1} and P_{m2}.

Experiment 6--The KCl beam splitter was positioned at a 15-deg angle of incidence with the alignment HeNe and a protractor. The EDCL was operated at about 500-W output power, and the power at P_{m1} and P_{m2} was measured and applied in the above expression.

This resulted in a measured beam splitter reflectivity of 0.06591, which agrees with the historic value, 0.068, to within a 3.1-percent error.

An alternate method to empirically determine the KCl reflectivity at this angle of incidence was performed.

Experiment 7--The laser was set up for an output power of 870 W. The KCl beam splitter was set at a 15-deg angle of incidence. The transmitted beam was collected and focused by an uncoated copper mirror. The transmitted power was measured by the 213 power meter with the KCl beam splitter in the beam train, and with the beam splitter removed from the beam train.

The measured transmitted power with the beam splitter in the beam train can be expressed as

$$P_{m2} = r_2 T_{bs} P_{out}$$

The measured transmitted power with the beam splitter out of the beam train can be expressed as

$$P^*_{mw} = r_2 P_{out}$$

The value of the KCl transmission will be given by the ratio of the transmitted power with the beam splitter in the beam train to the transmitted power with the beam splitter out of the beam train.

The average transmission calculated using the above technique was 0.9335 ± 3.2 percent, which gives a reflectance value of 0.0665 ± 3.2 percent. This reflectance value, using powers measured by the 213 power meter, agrees with the calculated reflectance value of 0.0686 to 3.1 percent.

The results of the two experiments described above indicate that the historic beam splitter reflection factor, 0.068, is valid to a 3.2 percent level of uncertainty.

Additionally, the beam splitter was checked by AFWL Metrology Laboratory for percent of transmission at a 15-deg angle of incidence over a range of wavelengths of about 10.6 μm. The results of this transmission test indicated that the particular KCl beam splitter used in the above experiments has a transmission of 0.932. This gives a reflectivity of 0.068, which agrees with the experimental results to within 2.2 percent.

TOTAL SYSTEM UNCERTAINTY

The total system uncertainty associated with the EDCL power measurement technique can be expressed as the square root of the sum of the squares of all elements contributing to the system error. For the EDCL power measurement technique, these elements are

a. Absolute accuracy of the 213 system: ±4.0%

b. Uncertainty due to 213 coating: ±3.0%

c. Uncertainty of split factor: ±3.2%

d. Beam splitter position: ±1.0%

e. Beam interference: ±2.0%

The total system uncertainty is ±6.34 percent.

CONCLUSIONS

The historic beam splitter reflection factor of 0.068 is valid to within 3.2 percent. The EDCL is not linearly polarized. The EDCL is stable, shot to shot, to within ±2 percent. Any errors due to the beam splitter positioning and beam interference are small and do not present a significant source of error in the power measurement. The greatest source of error is the absolute accuracy of the 213 power measurement system. The total system uncertainty is ±6.34 percent.

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